O BIOGÁS COMO FONTE DE ENERGIA PARA MOTORES DE COMBUSTÃO INTERNA: UMA REVISÃO

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RESUMO

O Biogás surgiu como uma tecnologia renovável prometendo converter resíduos de matéria orgânica em energia, entre os seus componentes, em termos de energia, o metano é a composição química mais importante, em particular para o processo de combustão em motores veiculares. A utilização de metano derivado dos resíduos de matéria orgânica dos aterros sanitários para substituir o combustível fóssil minimiza o impacto ambiental proporcionando uma redução significativa na emissão de gases de efeito estufa. Este artigo faz uma revisão dos aspectos ambientais, sociais e econômicos do biogás como fonte de energia, o processo de produção dessa energia renovável e o potencial do biogás produzindo energia para motores de combustão interna. Os estudos mostram que o biogás é um impulsionador de desenvolvimento regional e local de forma sustentável, pois a produção de biogás pode ser feita pelos próprios consumidores de energia, tornando-os autoprodutores e mais capazes de controlar insumos para suas atividades produtivas. Já para aplicações do motor, viu-se que ao adicionar uma certa proporção de H_2 ao biogás as propriedades de combustão podem ser melhoradas.

PALAVRAS-CHAVE: Biogás. Energia Renovável. Motores. Combustão Interna.

BIOGAS AS AN ENERGY SOURCE FOR INTERNAL COMBUSTION ENGINES: A REVIEW

ABSTRACT

Biogas has risen, as a renewable technology promising to convert litter organic substance into energy; among its components, in terms of energy, methane is the most important chemical component, particularly for the combustion process in vehicular engines. The use of methane derived from landfill organic matter waste to replace fossil fuel minimizes environmental impact by providing a significant reduction in greenhouse gas emissions. This paper reviews the environmental, social and economic aspects of biogas as a source of energy, the process of producing this renewable energy, and the potential of biogas in producing energy for internal combustion engines. Studies have shown that biogas is a driver for sustainable regional and local development, since energy consumers themselves, becoming producers, can product biogas and be better able to control inputs for their production activities. For engine applications, it has been found that by adding a certain proportion of H2 to biogas, the combustion properties can be improved.

KEYWORDS: Use until five (05) keywords by separating them with commas.

1 INTRODUCTION

Since the industrial revolution, the demand for energy has grown every year around the world, particularly in developing countries. According to Tolmasquin (2012), in Brazil, for the next decade there will be an increase of 5.3% in energy per year, reaching a 372 million tons of oil equivalent.

According to the National Energy Bulletin issued by the Ministry of Mines and Energy - MME, (2019), in 2018 the carbon dioxide (CO2) emitted in Brazil has reached 416.1 million tons of CO2 equivalent (Mt CO2-eq), being the transport sector accounted for 46.3% of this total, followed by the industrial sector, with 24.9%. Consequently, fossil fuels needed to be replaced by renewable and clean energy sources in order to reduce emissions of greenhouse gases and carbon dioxide (NAHAWI et. Al, 2010).

Globally, interest in biofuels is growing every day, being an alternative with regard to energy security, climate and poverty reduction; in addition, due to the growing global demand for energy and the annual depletion rate of the world quantity of oil reserves, which is 2.1%, there is an urgent need for energy sources other than fossil fuels, currently the main supplier of about 88% of global energy (DADA and MBOHWA, 2017).

These products are generated from available commom biomass sources and its application provides the circulation of carbon between air and fuel; in addition, problems such as greenhouse gas emissions and energy scarcity can be resolved simultaneously through this clean alternative. According to Qian et. al., (2017) most biofuels, such as biodiesel and ethanol, have adequate physico-chemical properties for effective combustion in internal combustion engines, with or without minor modifications. In particular, most biofuels contain a certain proportion of molecular oxygen that can help fuel combustion.

In fact, the application of biofuels in internal combustion engines (IC) is already successful. For example, bioethanol has been widely used as a renewable substitute for gasoline in spark ignition (SI) engines (GALBE AND ZACCHI, 2002; HANSEN et al. 2005). More recently, the preparation and application of biogas has been extensively studied (BOHUTSKYI and BOUWER, 2013; ESEN and YUKSEL 2013, ONWUDILI et al. 2013).

Jury et al. (2010) studied and compared the life cycle of biogas production and of natural gas. They found that, on human health and for the ecosystem, biogas is not very competitive with natural gas. However, biogas is competitive in relation to the effects of climate change, damage to resources and fossil energy demands.

Divya et. al., (2015) summarized the preparation of biogas of anaerobic digestion; they observed that the inventions of specialized multi-stage digesters allow the monitoring, sampling and control of the main parameters, such as pH, temperature and speed of loading, which is benefic for the conversion of biogas.

In relation to the great potential of large-scale production of biogas, research focused on the environmental, social and economic aspects of biogas as an energy source, combustion kinetics and applications in spark combustion engines. These issues have been widely studied under various operational conditions. Therefore, a review was made in this article, based on a series of published theoretical and experimental works related to these factors.

2 ENVIRONMENTAL, SOCIAL AND ECONOMIC ASPECTS OF BIOGAS

Biogas is a renewable energy source, as it can be produced with feedstocks that are renewed in a short time by some efforts of humanity as a whole. That is to say, only months or years, as it can be done with organic waste, for example. Among the environmental benefits, it is highlighted that biogas is an inducer of the proper destination and treatment of effluents and residues, thus reducing the risk of contamination of soil, air and water resources. The environmental aspects of biogas are very important also because their production is often motivated by the legal obligation to treat effluents and waste. Thus, in addition to the requirement for adequate treatment, there is the possibility of economic and financial gains with the production of energy from one of the treatment products. So, the process becomes more attractive and also causes positive environmental impacts (MARIANE, 2018).

Although after the biodigestion process the organic load of the effluent is reduced, reducing its impact potential; the nutrients commonly found in effluents and residues are not degraded and continue to compose the digestate. These nutrients, such as Nitrogen (N), Phosphorus (P) and Potassium (K) can cause eutrophication in water resources, that is, the proliferation of algae, causing an environmental impact on water bodies. At the same time, precisely because of its composition, the digestate produced in the anaerobic digestion process can be used as soil fertilizer, this way promoting increased productivity and reduced costs in agriculture. By reducing the demand for chemical fertilizers, indirect benefits are obtained, since, according to Costa and Silva (2012), they are commonly explored in mining areas far from agricultural areas, including in other countries, causing environmental impacts at the site and during production and transportation.

Another important benefit is the reduction of greenhouse gas (GHG) emissions. The concentration of these gases in the atmosphere has been increasing in recent decades, and researches correlate it to the increase in global temperature, which will bring many environmental, social and economic impacts to the planet. The production and use of biogas can promote the reduction of methane gas emission from landfills, as the biogas produced starts to be collected with greater efficiency and can be used to generate electricity. It can also promote the reduction of methane gas emissions from effluent storage ponds, since the part of the effluent that does not have contact with the surface air ends up being anaerobically digested, emitting methane into the atmosphere. At the same time, its use would allow the replacement of fossil fuels, such as diesel oil, natural gas and liquefied petroleum gas (LPG), with a renewable fuel in both the transport and the electricity generation sectors.

Biogas is an energy source widely distributed in the territory, unlike other sources that are highly concentrated. In fact, the feedstocks for biogas production is distributed both in urban, industrial and agricultural regions. According to Bley (2015), this characteristic allows energy to be produced close to its consumption and the demand for electricity and fuels from large power plants or distant locations is reduced, which increases safety, quality and energy efficiency, since energy (electricity and fuel) is now produced in a distributed manner.

This characteristic, however, can reduce the economy of scale, affecting the viability and attractiveness of the projects in several cases, as the plants are distributed in the territory, but many of them are of small scale. The consequence of this is that, in order to guarantee the viability of the projects, low cost technologies are often used for the production and use of biogas, reducing efficiency, quality and safety.

Among the social impacts of the production and use of biogas, Divya et al. (2015) mention the improvement in the quality of life of people around the systems by reducing odors and flies in the effluent treatment system.

The use of biogas for energy generation and digestate for soil fertilization allows the reduction of costs with the purchase of these inputs in rural properties, industries, sanitary landfills, sewage treatment plants or any other type of biodigestion plant. Another possibility is that these inputs are commercialized and can generate new sources of income for biogas plants. As mentioned by Bley (2015), in cases where the production of biogas is the focus of the business and not just the use of the residue of the productive activity, the biogas becomes a driver of new business. From an internal perspective , such as residences in very poor and / or isolated regions, the biodigestion of residues from family farming and its products can bring benefits such as access to energy and improve the quality of life for women and equality of gender. In these cases, women usually need to seek firewood daily for cooking food, which requires several hours of the day for this activity.

Another facet of this technology in agriculture may be the incentive for young people to stay in the rural area, since it is configured in a new productive activity and a new source of income. According to Bley (2015), the production of biogas can encourage the generation of jobs and the growth of the economy of the region where it is carried out, as it demands engineering, installation and maintenance services and inputs.

In addition, the production of biogas can be carried out by energy consumers themselves, making them self-producing and better able to control this input for their productive activities. However, the complexity of a biological process such as biodigestion stands out, which is influenced by aspects such as temperature, pH, homogenization, climate, characteristics of the substrate and others. The demand for biogas filtration to prevent equipment corrosion is yet another fact that increases the cost of projects. Thus, Jende et. al. (2016) indicate that there are several barriers and difficulties for the use of biogas to its full potential in Brazil.

Finally, according to Coimbra-Araújo et. al. (2014) biogas is not just a source of energy, but a mobilizer of regional development, as it can be produced with substrates from different productive and local activities, such as agriculture, industry, sanitary landfills and effluent treatment stations.

HOLOS
ISSN 1807 - 1600

3 BIOGAS AS ENERGY SOURCE

Biogas is produced in anaerobic degradation processes of organic matter. This process of anaerobic digestion occurs naturally with all organic matter that decomposes, for example, when there are accumulated residues that can be found in greater quantities in dumps, samitary landfills or in effluent storage ponds. So, using appropriate technologies, such as biodigesters, biodigestion can be applied in order to treat effluents or residues, produce biogas and / or produce biofertilizer (COIMBRA-ARAÚJO et al., 2014).

Among effluents and residues, we can mention urban sewage, the organic fraction of solid urban waste; swine, poultry and cattle production waste, animal slaughterhouses, starch mills, sugar and ethanol plants, among others.

Biogas is mainly composed of methane (CH4), carbon dioxide (CO2) and other gases present in low concentrations, such as hydrogen sulphide (H2S), hydrogen (H2) and nitrogen (N2). According to Qian et. al, (2017) the components of biogas can be divided into two categories: combustible components and non-combustible components. The fuel components are mainly CH4, CO and H2. The non-combustible components are mainly CO2 and N2. The presence of methane guarantees biogas the ability to be an energy source, allowing its use for the generation of electricity, heat production and production of biomethane and CO2.

Biomethane can be considered a gas similar to natural gas when its composition complies with ANP Resolution No. 08/2015, amended by ANP Resolution No. 685/2017 (ANP, 2015b; 2017). For this to happen, the biogas must go through a process of gas separation (upgrading) that causes the concentration of methane to rise from about 60% (molar base) to at least 96.5%. This Resolution was regulated for the national territory, with the exception of the North region, supplied by natural gas from Urucu, where the minimum concentration of methane in biomethane must be from 90.0 to 94.0% (molar base).

Related to that issue, Mariani (2018) states that the biogas production process basically involves the following steps: pre-treatment of the substrate; anaerobic digestion in the biodigester; digestate storage, treatment and recovery; treatment, storage and transport of biogas; application of biogas in the generation of electricity and / or heat; and production, storage and transportation of biomethane, as can be seen in Figure 1.

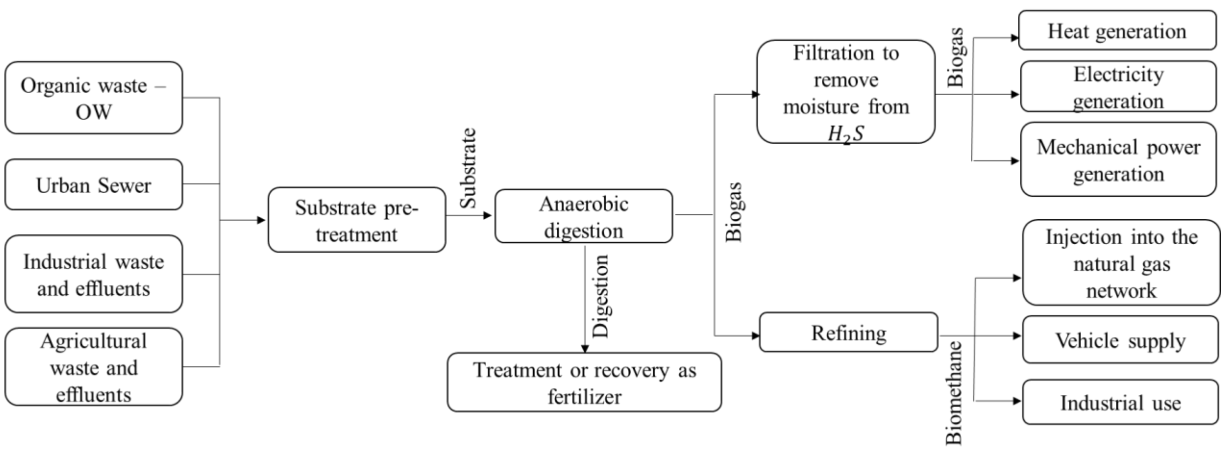

Figure 1 - Flowchart of biogas production and use. Source: Mariane (2018).

4 BIOGAS PRODUCTION PROCESSES

The use of anaerobic digestion in the treatment of organic waste is a good opportunity for many reasons that involve economic and environmental aspects (LETTINGA, 2001 and BARTON, et al. 2008). Anaerobic digestion is the collection of processes by which microorganisms decompose biodegradable material in the absence of oxygen (DADA and MBOHWA, 2017). Anaerobic digestion is mainly a biological mesophilic and hemophilic decomposition and stabilization of biodegradable residues under controlled anaerobic conditions, such as temperature, pH, retention time, etc.

The anaerobic process for the production of biogas from organic waste necessarily goes through four stages at the bacterial level, namely Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. The anaerobic digestion process is summarized in Figure 2.

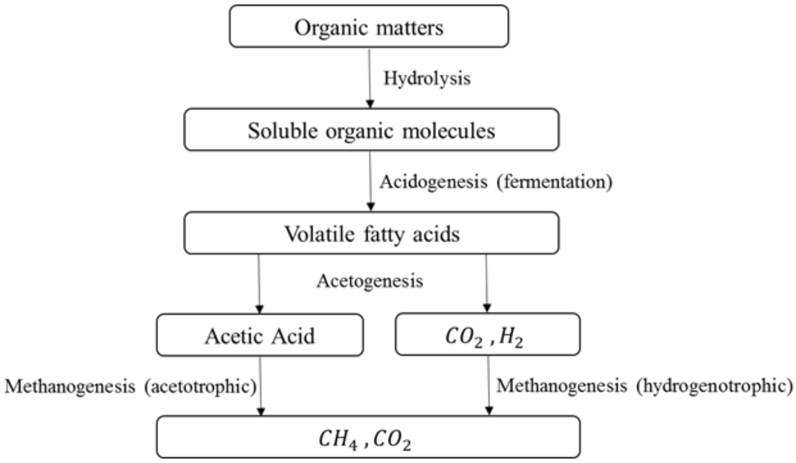

Figure 2: Anaerobic digestion via biochemical conversion. Source: Adapted Barton, et al. (2008)

The hydrolysis stage involves braking of large macromolecules of proteins, fats and polymers of carbohydrates (such as starch and cellulose) into aminoacids, long-chain fatty acids and sugars (BARTON, et al. 2008); in the acidogenesis phase occurs fermentation of small organic molecules produced in the hydrolysis stage, to form three, four and five volatile fatty acids, such as lactic acid, butyric acid, propionic acid, valeric acid and low alcohols (DADA and MBOHWA, 2017).

At the stage of acetogenesis the bacteria consumes the fermented products of the acidogenic phase to produce acetic acid, carbon dioxide and hydrogen (RAPPORT, et. al. 2012). This stage is followed by the process of methanogenesis, which is the final stage in which methane is produced as a result of the consumption of acetate, hydrogen and carbon dioxide. There are biochemical pathways used by methanogens to produce methane gas (BARTON, et al. 2008). The stoichiometries of general chemical reactions are shown in (1), (2) and (3).

Acetotrophic methanogenesis: $4CO_3COOH \rightarrow 4CO_2 + 4CH_4$ (1)

Hydrogenotrophic methanogenesis: $C0_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (2)

Methylotrophic methanogenesis: $4CH_2OH + 6H_2 \rightarrow 3CH_4 + 2H_2O$ (3)

5 APPLICATION OF BIOGAS IN INTERNAL COMBUSTION ENGINES

The low cetane value, combustion characteristics, such as the propagation flame speed, adiabatic combustion temperature and chemical reaction process of combustible components found in the biogas (CO, CH4 and H2) are quite different and the presence of inert gases (CO2 and N2) that have differences in heat capacity and have their influence on combustion, and they have a major impact on the overall performance of biogas. On the other hand, some factors such as the preparation technique and the sources of feedstock, can lead to the alteration of the biogas components, which is a great challenge for the large scale and efficient use of biogas in internal combustion engines (QIAN et al., 2017). For the reasons described above, many researchers have tried to use biogas with different components in internal combustion engines.

5.1 Biogas Application in Spark Ignition Internal Combustion Engines

As shown in Table 1, biogas is a type of high-octane fuel that can be easily used in the spark ignition engine (Qian et al., 2017).

Table 1 Comparison of the properties of LPG, natural gas and biogas.

Propriedade	GLP	Natural gas	Biogas
Composition	C_3H_8-30% C_4H_{10}-70%	CH_4-85% C_2H_6-7% C_3H_8-2% N_2-1% CO_2-5%	CH_4-57% CO_2-41% CO-0,18% H_2-0,18% Traces of other gases
Heating value less than 1 atm. and 15ºC (MJ / kg)	45,7	50	17
Density at 1 atm. and 15 °C	2,26	0,79	1,2
Flame speed (cm/s)	44	34	25
Stoichiometric A / F (kg in air / kg in fuel)	15,5	17,3	5,8
Lower flammability limit (% vol. In air)	2,15	5	7,5
Upper flammability limit (% vol. In air)	9,6	15	14
Octane number Researches Engine Auto-ignition temperature (ºC)	 103-106 90-97 406-450	 120 120 540	 130 - 650

Source: Yadav et al, (2013)

Researchers used the main biogas groups to study the combustion and emission characteristics of the biogas engine. According to Whiston et al. (1902) the turbulent combustion speed of CH4 / CO2 was calculated with a two-zone combustion model of a spark ignition engine. The results show that with the increase in the concentration of CO2, the rate of turbulent combustion reduced by 50% when 30% of CO2 was used in the fuel. Anand et al. (2006) used artificial neural networks to calculate the efficiency and NOx emissions of positive-ignition engines under different equivalence ratios and compression ratios with CH4 / CO2 such as biogas. They found that with the increase in the concentration of CO2 in the biogas, NOx emissions can be effectively inhibited, and the rate of volume of CO_2 can help to inhibit engine beat. Shigarkanthi et al. (2005) studied the effects of the equivalence ratio and loads on the cyclic engine varying with biogas as fuel in a spark ignition engine. At the same time, based on the two-zone model, they developed a complete cycle calculation program to calculate the impact of CH emissions cycle changes.

In addition, some researches have attempted to study biogas directly under laboratory conditions. For example, Yadav et al. (2013) studied the emissions of biogas as fuel in positive ignition engines. Studies have shown that the composition and molecular structure of biogas has made it a low emission fuel, thus CO emissions can be neglected, and CH and NOx emissions are significantly reduced. However, carbon dioxide emissions have increased, especially without biogas purification. Porpatham et al. (2013) studied the influence of volute on the combustion and performance of the spark ignition engine using biogas as fuel. They found that increasing the cylindrical volute could increase the limit of diluted biogas fuel and accelerate flaring. At full load, CH emissions decrease, but no emissions increase with increasing volute. Papagiannakis et al. (2013) used a two-zone phenomenological model to simulate the effect of the compression rate and the ignition point on combustion and emission characteristics in a spark-ignited heavy-duty turbo engine using wood and gas as fuel. They found that increasing the compression ratio and improving the ignition time can improve efficiency. However, at the same time, there is a maximum increase in cylinder pressure. In addition, increasing the compression ratio will increase no emissions, especially under poor mixing conditions.

Due to the high relationship between the inert gas, the heat value and the flame speed of the biogas propagation, it leads to the instability of the combustion of the fuel mixture when supplied with biogas. In contrast, hydrogen (H_2) has a high fast flame propagation speed. That is to say, a certain proportion of H_2 added to the biogas can increase the flame propagation speed, which is beneficial for combustion stability. Chen et al. (2012) used H_2 / CO as a fuel in a spark ignition engine and used CO_2 as a diluent to study the combustion and biogas emission characteristics. They found that increasing the concentration of H_2 can improve the speed of propagation of the flame, and the rate of heat release is more concentrated. In addition, the volume heat value of the mixed gas is reduced, which is useful for reducing NOx and temperature emissions. When using CO_2 dilution with increasing dilution ratio, the average pressure is effective and the thermal efficiency will be decreased. Besides, the variation of the motor cycle will increase, and the increase in the percentage of H_2 can be used to inhibit the variation of the cycle. Chung et al. (2013) studied, by numerical simulation, the performance of the combustion of H_2 / biogas in an ignition engine. The study concluded that the peak pressure velocity and heat release values increased and the cylinder delay time was reduced with an increase in H_2 content. Porpatham et al. (2007) analyzed the influence of different equivalence ratios on the performance of the ignition engine fed with biogas mixed with 5%, 10% and 15% of H_2. The study showed that, with the increase in the H_2 content, the burning rate increases and the levels of low combustion temperature load have also increased. When the proportion of H_2 was greater than 15% and at a high equivalence ratio, the ignition point must be delayed to avoid knocking, and the thermal efficiency has been reduced. Rakopoulos et al. (2009) used an almost dimensional multi-zone model to study the combustion of biogas/hydrogen in a single cylinder engine to analyze the thermodynamic progress in detail; They concluded that the addition of increasing amounts of H_2

HOLOS
ISSN 1807 - 1600

in the biogas results in a decrease in the period of flame development. Park et al. (2011) studied the characteristics of biogas mixed with hydrogen in a spark ignition engine on performance and emission. They found that the inert gas in biogas can improve thermal efficiency and reduce NOx emissions. In addition to improving combustion stability, H2 can extend the low temperature range and reduce CH emissions, but NOx emissions are increased. Besides, the loss of heat transfer increases with the increase of H2, which decreases the thermal efficiency. Research shows that when the volume fraction of H2 is between 5% and 10%, thermal efficiency is higher. Park et al. (2012) studied the effects of EGR on the efficiency and emissions of an ignition engine using biogas/hydrogen as a fuel. It has been found that hydrogen can be used to improve the combustion stability of biogas, but the high temperature of the adiabatic flame can lead to higher levels of NOx emissions. Increasing the EGR rate will increase the heat capacity of the cylinder, which decreases the final compression temperature. This not only increases the ignition delay time, but also decreases the flame propagation speed and the combustion temperature. Therefore, as the EGR rate increases, combustion stability is reduced, MBT ignition regulation is increased, and THC emissions are higher, as NOx generation levels are reduced. With the increase in EGR, although combustion efficiency decreases slightly, thermal efficiency is increased due to decreased pump loss and loss of heat transfer.

To test further on the use of biogas in positive-ignition engines, some scholars have compared the combustion and emission of biogas with commercial fuels. Karlsson et. al. (2008) studied the relationship between conventional gasoline, compressed biogas (CBG), Swedish summer (E85) and winter fuel ethanol in a CNG / gasoline car and an ethanol / gasoline passenger car . They found that for the CNG / gasoline vehicle, CBG fuel led to a decrease in energy consumption and NOx, PM and PN emissions, but CH4 emissions increased compared to gasoline. Yadav et al. (2013) compared the effects of gasoline, purified biogas and biogas on the performance of the ignition engine by increasing the compression ratio and optimizing the ignition point. They found that higher proportions of CO2 and other non-flammable gases in the biogas reduced the efficiency of the gas engine. Maximum engine power has decreased and fuel consumption has increased (Lee et al. 2010). In relation to combustion and emission characteristics of natural gas, biogas and biogas / H2 under different EGR values with ideal ignition times based on the maximum efficiencies obtained with a gas engine. As shown in Fig. 3, NOx emissions and efficiency normally decreases with increasing EGR. When fed with biogas, NOx emissions were decreased dramatically compared to the use of natural gas. With the addition of hydrogen to the biogas, both the engine's NOx emissions and efficiency increased. It can be concluded that there is a combination between the exhaust gas recirculation and the optimal ignition point. The use of hydrogen / biogas fuel mixtures should lead to significant improvements in terms of generation efficiency and NOx emissions from the biogas engine.

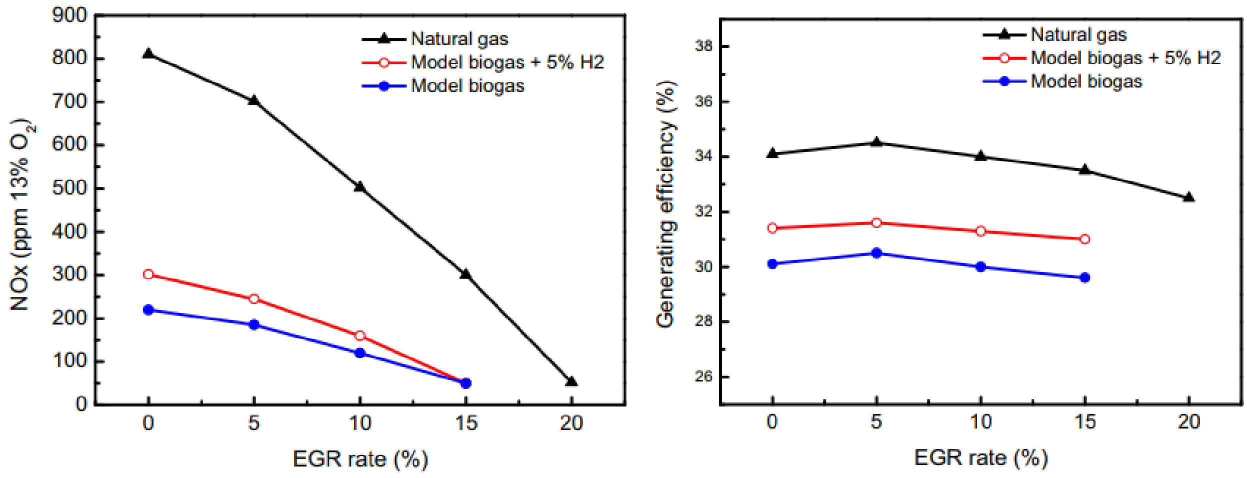

Figure 3: Effect of EGR on NOx emissions and efficiency of a spark ignition engine with biogas / hydrogen as fuel.

Source: Lee et al. (2010)

6 FINAL CONSIDERATIONS

Biogas is an interesting renewable biofuel for use in spark-ignition internal combustion engines because of its advantages. In this review, research on the benefits of using biogas, the chemical kinetics of the process and the use of biogas in internal combustion engines were summarized. Based on this review, the following conclusions can be reached:

Among the environmental benefits, biogas is an inducer of the proper destination and treatment of effluents and waste, reducing the risk of contamination of soil, air and water resources. The environmental aspects of biogas are very important because their production is often motivated by the legal obligation to treat effluents and waste and with the requirement of adequate treatment, there is the possibility of economic and financial gains with the production of energy from one of the treatment products.

Among the social impacts of biogas production and use, we can highlight the improvement in the quality of life of people around the systems by reducing odors and flies in the effluent treatment system. The production of biogas can encourage the generation of jobs and the growth of the economy in the region where it is carried out, as it requires engineering, installation and maintenance services and inputs. This characterizes biogas not only as a source of energy, but as a mobilizer of regional development.

The presence of methane guarantees biogas the ability to be an energy source, allowing its use for the generation of electricity, heat production and in the production of biomethane and CO2. To do this, the biogas production process basically involves the following steps: pre-treatment of the substrate; anaerobic digestion in the biodigester; digestate storage, treatment and recovery; treatment, storage and transport of biogas; application of biogas in the generation of electricity and / or heat; and production, storage and transportation of biomethane.

The anaerobic process for the production of biogas from organic waste necessarily goes through four stages at the bacterial level, namely Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis.

Biogas has a lower flame speed and heating value than natural gas and a higher auto-ignition temperature than that of LPG and natural gas and that these characteristics have great influences on the application of biogas in spark ignition engines .

The main challenge of the large-scale application of biogas comes from the instability of its components, which is due to the differences in the production process and the types of feedstocks. These differences cause two problems. First, because of the complexity of biogas compositions, a lot of basic research is needed to analyze different components, with different proportions and to establish a detailed kinetic model. Second, the instability of the biogas makes it difficult to effectively control the combustion of the engine. Engine control software must be required to adapt to changes in the composition of biogas.

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